UNDERSTANDING LOCA-RELATED DUCTILITY IN E110 CLADDING

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Numerous investigations performed in recent years have shown that cladding alloys based on Zr-Nb are the most advanced materials for achieving fuel cycles with high burnup in light water reactors.

The operating experience of VVER-type Russian reactors employing the E110 alloy (Zr-1%Nb) for the fuel rod claddings indicates that material of this type (in contrast to the alloy of the Zircaloy type) allows the cladding to retain ductility at fuel burnup up to 60 MWd/kgU, inclusive. Moreover, according to the results of in-pile tests, the existing ductility margin proved to be sufficient to retain a high failure threshold with no fragmentation (>130 cal/g) under reactivity-initiated-accident (RIA) conditions. Besides, experiments of the "thermal shock" type performed in A.A. Bochvar All-Russian Research Institute of Inorganic Materials to validate the mechanical behavior of oxidized irradiated E110 cladding under loss-of-coolant-accident (LOCA) conditions have demonstrated that the threshold of its fragmentation corresponds to the license safety criteria currently in force (1200 C, 18%) with a reasonable margin.

Nevertheless, an assessment of experimental methods to validate the mechanical behavior of oxidized Zr-Nb cladding under the LOCA conditions has become the subject of a broad international discussion launched within the context of such issues as the reassessment of the safety criteria, the representativity of different types of tests for the validation of mechanical behavior of fuel rods under the accident conditions, and so on.

In this case, a detailed consideration of results of previously performed research with Zr-1%Nb alloys has shown that more thorough mechanical tests should be carried out to examine the zero ductility threshold of oxidized E110 cladding. An appropriate program was developed by Russian Research Center "Kurchatov Institute" in cooperation with Russian State Research Center "Research Institute of Atomic Reactors" with the support of Joint Stock Company "TVEL" (Russian Federation), US Nuclear Regulatory Commission (USA), and Institute for Radiological Protection and Nuclear Safety (France).

Ring compression mechanical tests were selected as the basis for the first stage of the work because this approach has a good historical tradition and offers the prospect of direct comparison of results as a function of cladding material and oxidation parameters.

The developed program of oxidation and ring compression tests included two subprograms:

1. Determination of the zero ductility threshold of the cladding versus such parameters of the oxidation scenario as heating and cooling rates under the following fixed conditions:

- material of cladding (E110 unirradiated tubes);
- double sided oxidation with steam at 1100 C;
- ring compression tests at 20 C.

2. Determination of the sensitivity of the zero ductility threshold for a fixed combination of heating and cooling rates to the following parameters:

- material of cladding (E110, E110K, E635, Zry-4);

- temperature of oxidation (1000–1200 C);
- temperature of mechanical tests (20-300 C);
- irradiation of cladding (unirradiated E110 claddings and refabricated irradiated E110 claddings from commercial fuel rods with burnup ~50 MW d/kg U).

Results of the first subprogram presented in Fig. 1 show the following:

- the transition of the oxidized cladding from a high ductility state to an embrittlement one happens suddenly in the narrow range of the ECR (Equivalent Cladding Reacted);
- critical values of the ECR (7.6-9.2) corresponding to those of the zero ductility threshold are relatively independent of the combination of heating and cooling rates.

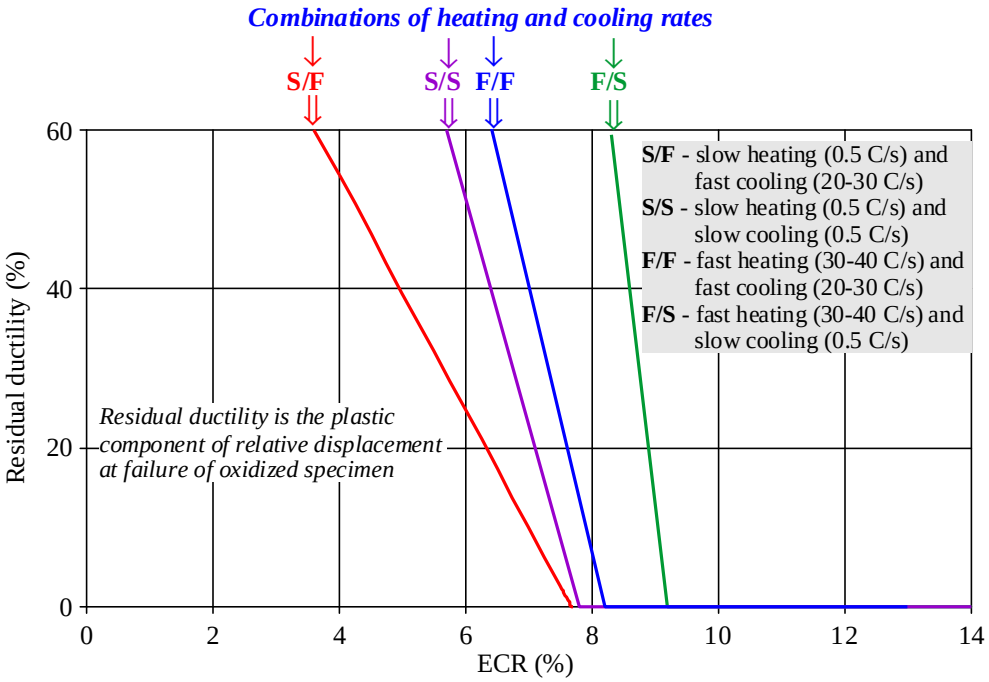

Fig. 1. Residual ductility of unirradiated E110 cladding oxidized at 1100 C as a function of ECR for various heating and cooling rates.

Further research performed within the context of both subprograms revealed the following:

- typical consequences of the breakaway effect were visually observed on the surface of E110 cladding in the range close to critical values of the ECR;
- hydrogen concentration in the E110 oxidized cladding achieved 700 ppm under zero ductility conditions.

The comparative analysis of E110 and Zry-4 claddings confirmed that:

- differences in alloy composition of these two alloys determined different oxidation behavior of E110 and Zry-4 claddings (see Fig. 2);
- the zero ductility threshold of Zry-4 oxidized cladding was about 13% (ECR as measured).

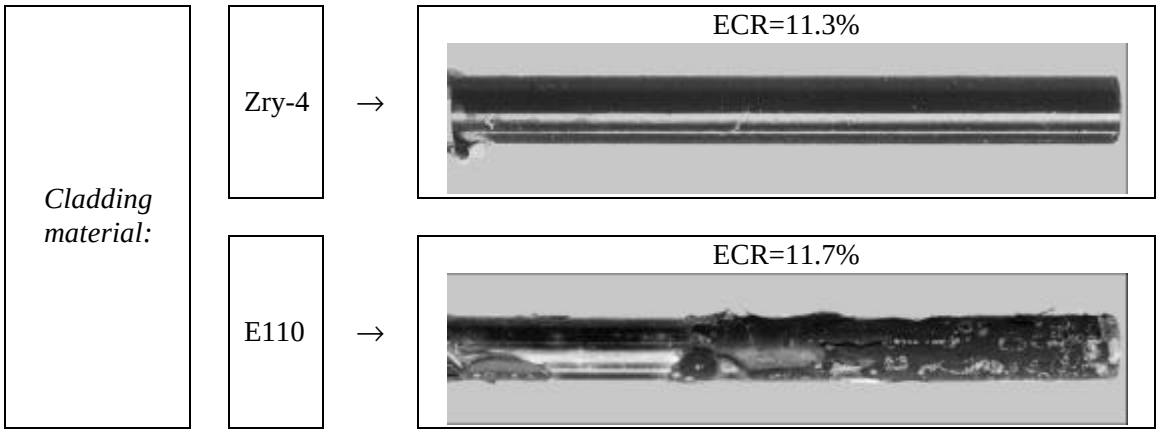

Fig. 2. Appearance of E110 and Zry-4 claddings after the oxidation at 1100 C.

To clarify the effect of alloy composition and oxidation conditions, the next part of the program was focused on the comparative tests with E635 cladding, E110K cladding (increased oxygen concentration), and one-side oxidized E110 cladding (for the comparison with the published data on M5 ring compression test results). This part of the work is in process now, but the results already obtained allow to note the following:

- significant differences were not seen in the mechanical behavior of E110 and E635 oxidized claddings;
- one-side oxidation of E110 cladding led to an increase of the zero ductility threshold up to 12% ECR (from 8.2% for double- side oxidation).

Separate important lines of the program were devoted to studies of the sensitivity of the E110 oxidized cladding mechanical behavior to irradiation, temperature and the type of mechanical tests.

These studies have demonstrated that:

- the zero ductility threshold of irradiated E110 oxidized cladding is not less than the embrittlement threshold of the unirradiated cladding;
- an increase in the temperature of ring compression tests from 20 C up to 135 C results in an increase in the critical value of ductility up to an ECR=12% (apparently, due to the temperature influence over the hydride behavior);
- special reference tensile mechanical tests performed with the E110 oxidized cladding confirmed that:
  - ⇒ there are no contradictions between the zero ductility thresholds determined in compression tests and tensile tests;
  - ⇒ the zero ductility threshold is a function of the temperature of the mechanical tests.

Thus, preliminary results of this program reveal several factors that are important for understanding LOCA-related ductility of the E110 cladding. But additional work must be completed to obtain the experimental data base that is necessary to reach conclusions on this issue.